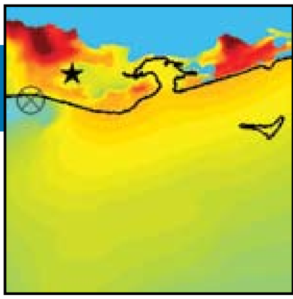

Advanced Surge and Inundation Modeling: A Case Study from Hurricane Katrina

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The storm surge and inundation from Hurricane Katrina that devastated Gulf Coast communities on August 29, 2005, presented an opportunity to evaluate and advance coastal ocean modeling capabilities at NRL and within the Navy. A highly realistic simulation of Katrina's storm surge and inland inundation was developed using the ADvanced CIRCulation (ADCIRC) model. The finite-element basis of ADCIRC is advantageous in its utilization of unstructured triangular grids. The "Katrina" grid contains 375,479 computational points and 730,431 triangular elements with 225 m spatial resolution in coastal and inland areas, resulting in the largest Navy application of unstructured grid models to date. Comparison between the model-computed high water values at measured high water mark locations along the Gulf coast indicate very good agreement between observed and predicted water levels with average errors of just over one foot. NRL recently transitioned the ADCIRC model to fleet operations for coastal predictions and remains an active ADCIRC development partner.

INTRODUCTION

Throughout modern history, amphibious assaults and landings have been a mainstay of U.S. Navy operations. The vulnerability of landing craft to capsizing, swamping, stranding, and filling with sand and water was clearly realized following a post-World War II review of amphibious operations. Many amphibious landing problems and casualties during World War II were attributed to the waves, currents, and water levels of the local environment. Similar problems occurred during the Korean War. Following the major invasion of Incheon Harbor, a U.S. Navy Tank Landing Ship was stranded during low tide near the tidal basin on Incheon's waterfront on September 20, 1950.

More than fifty years later, the Navy still finds inundated environments challenging for operations. Since the declaration of the Global War on Terrorism following the events of September 11, 2001, military operations are increasingly focused on special operations that take place in coastal environments such as estuaries, shallow waterways, and inland rivers. Inundation in these operational theatres is typically caused by extreme tidal ranges, rainfall-induced flooding events, and/or wind-generated setup. These occurrences directly affect the insertion and movement of Naval Special Warfare (NSW) forces, who routinely operate in environments for which the only know information may be an outdated, perhaps 30-year-old topographic map. Areas subject to inundation processes are often located at the cusp of the land-sea interface where algorithms for processing satellite imagery break down or are sub-optimal.

Inundation from storm surge is a particular concern for stateside Navy installations. The two major homeports for the U.S. Navy's east coast fleet are at Norfolk, Virginia, and Mayport, Florida, both vulnerable to landfalling Atlantic hurricanes. A decision to relocate the Norfolk harbor fleet, for example, could cost $5 million and would need to take place three days in advance of a predicted landfall in order to recall personnel and to ready ships in maintenance or overhaul for evacuation. Most recently, the Navy base at Pascagoula, Mississippi, on the Gulf of Mexico was directly impacted by the landfall of Hurricane Katrina on August 29, 2005.

As we now know, Naval Station Pascagoula was not alone in registering effects from Hurricane Katrina. The devastation to Gulf Coast communities on August 29, 2005, far exceeded all previously recorded storm events. The extent of storm damage to the coastal states of Louisiana, Mississippi, and Alabama categorizes Katrina as the most destructive and costliest natural disaster in the history of the United States. According to the National Oceanic and Atmospheric Administration (NOAA), the storm surge along the Mississippi coast was the highest ever recorded in the United States. Naturally, the location of NRL-Stennis Space Center (Bay St. Louis, Mississippi) directly in the path of the storm motivated NRL's interest in developing a hindcast representation of Katrina's surge and inland inundation. The events precipitated by Hurricane Katrina provide an invaluable opportunity to evaluate the Navy's capability to predict coastal surge and inundation and to direct future developments that enhance such a capability.

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THE SURGE MODEL

Tropical storm and hurricane events can cause a significant rise in coastal sea level when strong winds combine with low barometric pressure. Storm surge forms as winds push elevated sea levels into shallow coastal waters. Winds directed onshore form a "wall of water" that moves towards the shoreline and eventually washes inland, leaving previously dry land covered with water (inundated). For a surge model, then, forcing is derived principally from wind, though tidal effects are also important as they can magnify the height of the surge. The amount of wind energy that translates to the ocean surface is determined by the drag force at the air-sea interface. Surface waves are also generated at this interface but their effects, while significant, are not considered here. Movement of the water is further modulated by frictional effects at the seabed and over land. All of these processes can be represented mathematically to form a numerical model for surge and inundation.

A numerical model predicting surge and inundation computes water height and movement (currents) in the coastal ocean and over inland regions. One such model used widely within the Army and Navy communities is the ADvanced CIRCulation model, ADCIRC (http://adcirc.org).[1] ADCIRC has its basis in the well-known, two-dimensional, vertically integrated shallow water equations. The discrete forms of these equations within ADCIRC use a finite element approach, which is particularly well suited to application in complex coastal regions. When using finite elements, the computational mesh is composed of variably sized triangles whose density can vary throughout the modeled region. The range of element density can span several orders of magnitude, lending tremendous flexibility to the construction of a computational mesh. Within a single mesh it is possible to resolve fine-scale features or gradients in the underlying seabed elevations (bathymetry) and/or overland elevations (topography), to represent the complexities of the shoreline and to allow for open ocean boundaries that are remote relative to the coastal area of interest. The inundation of dry land areas is handled by activating and de-activating grid elements using criteria based on a simplified momentum balance between the pressure gradient and bottom friction. The frictional resistance in very shallow water is designed to increase as the depth decreases.

The ADCIRC model is also designed to be portable across various computational platforms and is highly efficient, harnessing the latest parallel processing paradigms to speed the time to solution. The ADCIRC model has a successful history of predicting tides and storm surge spanning nearly fifteen years and is, in fact, the surge model that the Interagency Performance Evaluation Taskforce (IPET) applied to the recent performance evaluation of the New Orleans and southeast Louisiana hurricane protection system following Hurricane Katrina.

A HINDCAST RECONSTRUCTION OF HURRICANE KATRINA

NRL began a reconstruction of Katrina's storm surge three weeks after the storm, with a focus on events along the Mississippi Gulf Coast. The initial step was the creation of a computational mesh. The importance of a quality mesh cannot be understated. To accurately represent the surge and inundation it is necessary to resolve fine-scale changes in bottom slope, details of the coastline, and other geographic features such as islands, inlets, and channels, while simultaneously preserving properties of the triangular elements that promote model stability and retaining a computationally viable problem (i.e., a timely solution). Software developed at NRL for semi-automated mesh generation constructs an unstructured finite element mesh using refinement criteria based on specified bathymetric/topographic values and constrained by the coastal boundary points. Several iterations and manual interventions were necessary to obtain the final unstructured finite element mesh designed to capture Katrina's storm surge and inland inundation; this mesh consists of 375,479 nodes and 730,431 triangular elements, the largest Navy unstructured grid model application to date (Fig. 1). The mesh centers on the northern Gulf Coast region encompassing inland areas, but also includes the entire Gulf of Mexico and extends out into the western North Atlantic Ocean. Such an expansive domain allows the surge to naturally build up within the modeled region as the hurricane moves from the deep ocean into coastal waters. Furthermore, ocean boundaries in deep water are subject to minimal surge and inverted barometer effects and can appropriately accept tidal forcing from a global tide model. These boundaries also are far removed from the coastal area of interest. The targeted spatial resolution of the mesh near the coast and inland is 225 m. The final mesh used for the hindcast of Katrina represents a balance between the desire for fine-scale resolution and the need for stability of the inundation algorithm, and accounts for computational constraints imposed by the necessarily small time-step integration.

To drive the surge model, the best available wind forcing was produced at NOAA's Hurricane Research Division (HRD) at the Atlantic Oceanographic and Meteorological Laboratory (AOML) through the HRD Real-time Hurricane Wind Analysis System (H*Wind) project. The H*Wind product is an integrated tropical cyclone observing system that uses wind measurements from a variety of observation platforms to develop an objective analysis of the distribution of wind speeds in

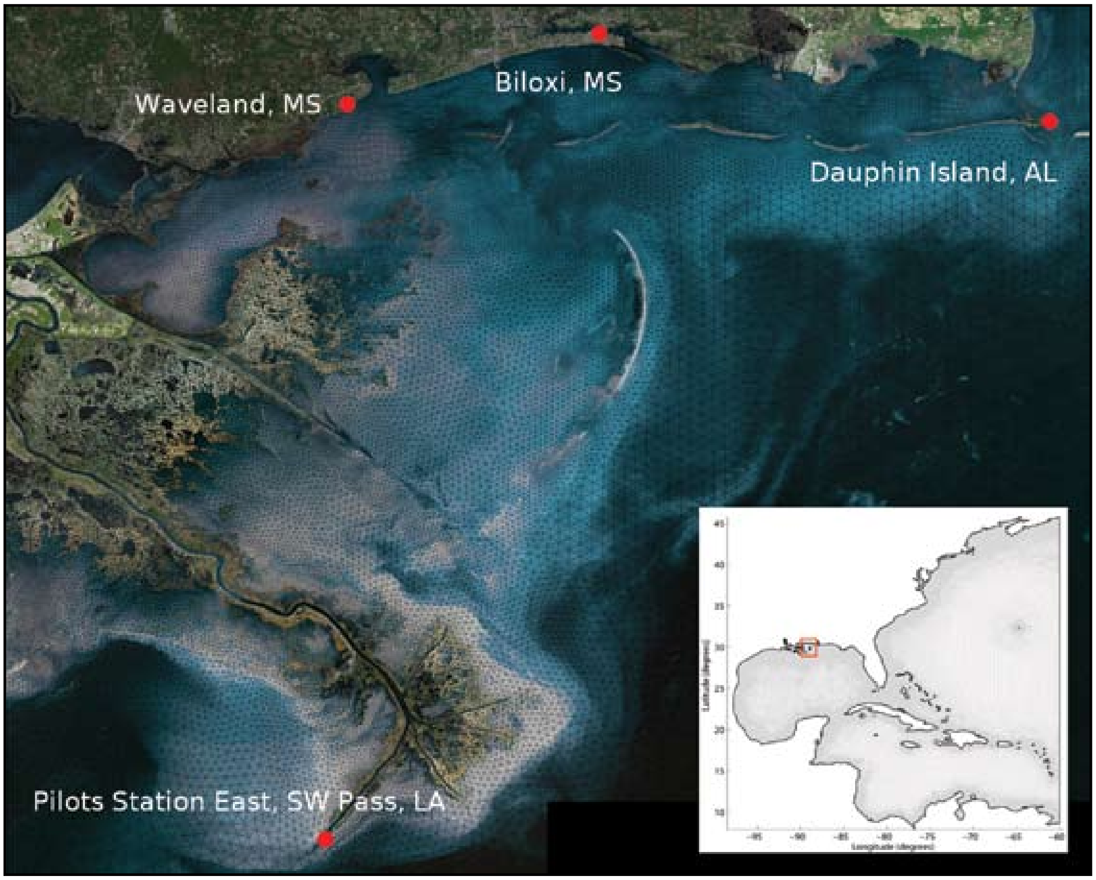

FIGURE 1
The density of the triangular elements in the northeast Gulf of Mexico contained in the computational mesh for the entire model domain (inset) overlays a true color satellite image that distinguishes land from water.

a hurricane.[2] The wind fields are typically constructed from a real-time analysis of flight-level reconnaissance data, satellite observations, pressure-wind relationships, and available surface data. We interpolate the three-hourly H*Winds using an approach that follows the storm center to preserve the integrity of the storm as it moves in time, and we further downscale the wind fields to fifteen-minute intervals. The time-interpolated wind fields are spatially interpolated to the computational mesh and then converted to wind stress. The wind drag at the sea surface is simply specified as a constant and with no distinction between winds over land or water or the directional history of the wind.

In addition to surface winds, tidal forces are applied, including those that act on the modeled body of water (tidal potential) and those caused by tides entering the domain at the open ocean boundary. At the deep ocean boundary, tidal forcing is applied at frequencies of the daily (K_1, O_1) and twice-daily (M_2, S_2, and N_2) tides obtained from the Grenoble global tidal model. The tidal potential is applied on the interior of the domain for the same constituents.

The hindcast simulation of Hurricane Katrina storm surge began August 27, 2005, following a ramp-up period of 15 days during which all forcings were gradually applied until full strength was reached at the end of the ramp-up phase. By this time in the simulation, Hurricane Katrina had crossed the state of Florida and had entered the warm waters of the Gulf of Mexico (Fig. 2). Katrina was past its peak intensity by the first landfall near Buras, Louisiana, at 6:10 a.m. CDT (1110 UTC) on August 29; a second landfall near the Louisiana/Mississippi border occurred about 9:45 a.m. CDT (1445 UTC) on August 29. The model hindcast of surge and inundation ended at 5:00 a.m. CDT (1000 UTC) on August 30, which coincided with the last available H*Wind product contained within the mesh. At every 1-second time integration of the model, the water levels and depth-integrated currents are computed by the ADCIRC model at all points in the model domain.

EVALUATION

The surface winds from Hurricane Katrina at 10:00 a.m. CDT (1500 UTC) on August 29, 2005 (Fig. 3) and the resulting storm surge computed by the ADCIRC model for the same time and date (Fig. 4) are presented. Surge heights well over 20 feet at the coastline

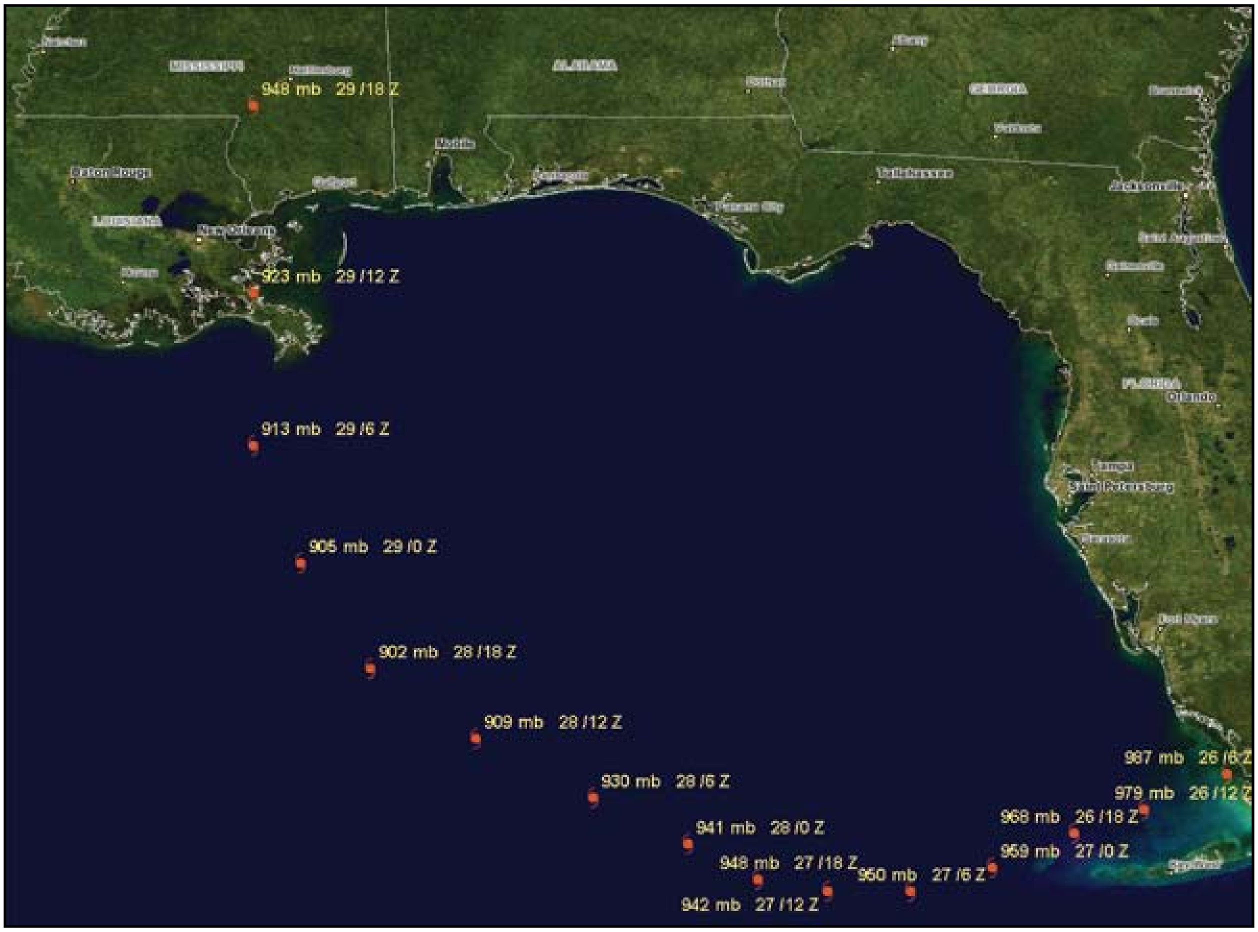

FIGURE 2
The track of Hurricane Katrina at 6-hour intervals once the storm entered the Gulf of Mexico off the west Florida coast at 0600 UTC (6Z) on 26 August 2005 with central pressure of 987 mb. The final location of the storm at hurricane strength occurred in southern Mississippi at 1800 UTC (18Z) on 29 August 2005 with a central pressure of 948 mb.

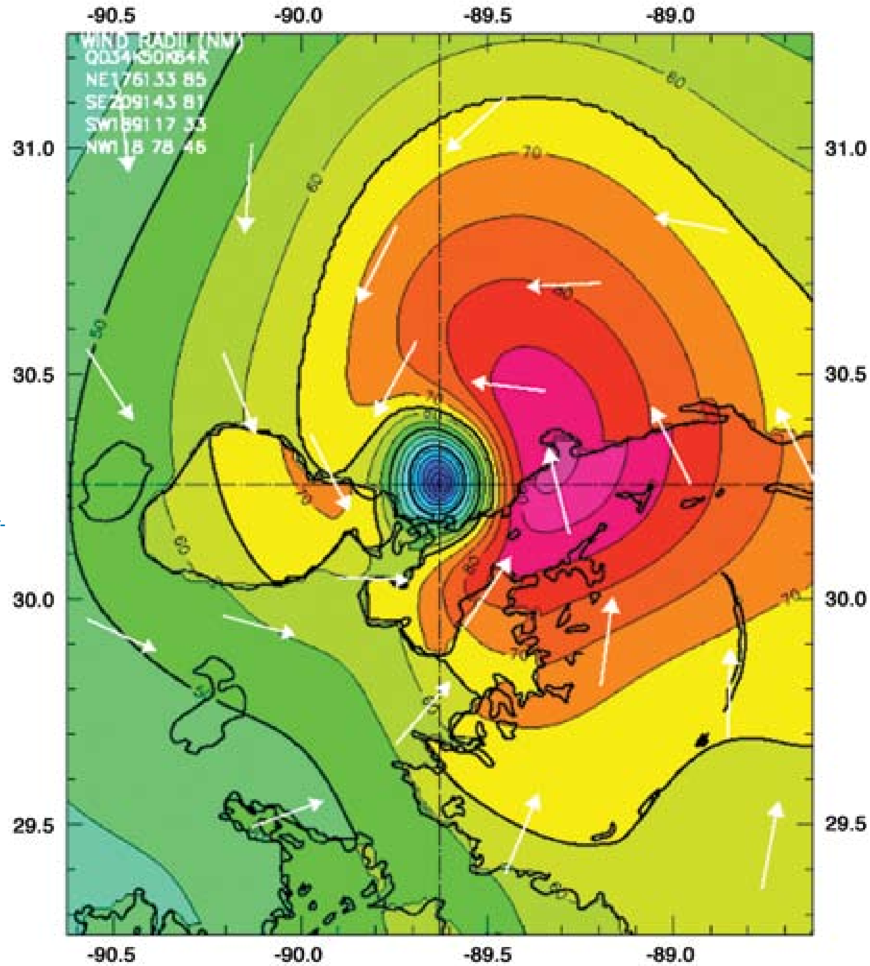

FIGURE 3
The magnitude (color) and direction (arrows) of the maximum 1-minute sustained surface winds in knots for Hurricane Katrina at 10:00 a.m. CDT (1500 UTC) on 29 August 2005 (courtesy of the NOAA Hurricane Research Division).

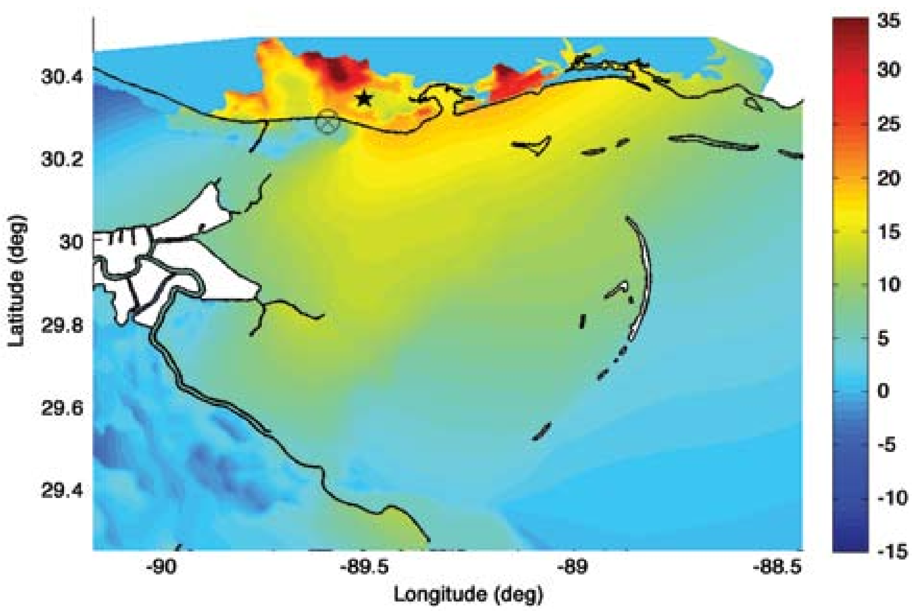

FIGURE 4
The ADCIRC model-computed storm surge and inland inundation elevation in feet for Hurricane Katrina at 10:00 a.m. CDT (1500 UTC) on 29 August 2005. The coastal outline is shown in black. The storm center is shown by a circled X and the location of Stennis Space Center, Mississippi, is marked with a star.

on the right side of the storm reflect not only the strength of the storm winds at the time of landfall but also the buildup of surge that occurred prior to landfall. Even higher water levels are shown inland (near Waveland, Mississippi, and west of Biloxi, Mississippi) as the large radius of hurricane winds easily pushed water over the gently sloping coastal lands. Timing of the inundation indicates that areas to the west of Waveland, Mississippi, including the northern coast of Louisiana (Slidell), inundated first as hurricane winds pushed water into the bays and up the rivers. Not until landfall did the Mississippi Gulf coast west of Biloxi experience its peak flooding. Note that even after landfall (Fig. 4), sea levels remain elevated throughout the coastal waters. For some areas far inland, particularly at the wetting front, excessive inland flooding (over 30 feet) is computed. Analyses of these hindcast results have revealed limitations in the inundation mechanism within the ADCIRC model that prevent rapid advancement of a wetting front and complete drainage of the flood water following peak storm winds (evidence of this is northwest of Stennis Space Center, Mississippi).

Timing of the wetting front is difficult to validate since observations are often limited. However, the modeled water heights are compared to recorded elevations at three observing stations that survived the storm: Pilot Station East, Southwest Pass, Louisiana; Waveland, Mississippi; and Dauphin Island, Alabama (Fig. 5). In each case, the agreement between the modeled and observed water levels is quite reasonable. The phasing of the tides and peak surge computed by the model are lagging the observed values by no more than a couple of hours and the model's underprediction as the storm nears its landfall position is likely due to the neglect of surface wave effects.

Evaluation of the modeled magnitude and extent of surge and inundation is accomplished by comparing computed high water mark values to high water marks measured by the U.S. Geological Survey (USGS) shortly after the storm. At each location in the mesh, the highest water level from the model (evaluated at every 1-second model time-step) is recorded and shown in Fig. 6. Of 458 high water mark stations, 315 were wetted in the model. Red dots on the map in Fig. 7(a) indicate 143 locations that did not experience inundation during the hindcast simulation of Hurricane Katrina. It is likely that a number of factors contribute to this type of error, such as erroneous values for local water depth and land height, not accounting for the decreased wind drag over water, or limitations in the inundation mechanism as previously cited. Despite the non-wetting of certain locations, the model-computed water elevations at the remaining 315 high water mark locations had an average error of only 1.2 feet (Fig. 7(b)). Stations with the largest errors underpredict water levels and are found near those same locations that remained erroneously dry. These results are extraordinary, given the intent of the hindcast to use an available predictive capability and information on water depth, land height, and wind strength at a level of detail typical for Navy operations in non-U.S. waters.

DEVELOPMENT OF A SURGE AND INUNDATION PREDICTION CAPABILITY

The proximity of Katrina's landfall to the Navy's Oceanographic Operational Center at NAVOCEANO, Stennis Space Center, Mississippi, reignited Navy interest in a robust capability for storm surge prediction. Different from a hindcast exercise, Navy applications require *forecast* hurricane wind fields. While real-time H*Wind products are available for storms impacting U.S. waters, this product cannot address inundation events along foreign coasts. Operationally available Navy-generated wind products such as the Navy Operational Global Atmospheric Prediction System (NOGAPS) and the Coupled Ocean Atmospheric Prediction System (COAMPS™) do not contain an embedded hurricane model, so do not provide accurate storm track and/or intensity of a hurricane. To address the need for realistic forecast hurricane winds, the parametric cyclone model of Holland was selected.[3] While not perfect, the cyclone model contains to first order the physical mechanisms of tropical storm generation and propagation. Forecast wind fields from the Holland model, based on known or projected track information, replicate with reasonable fidelity the intensity, size, and forward speed characteristics of a landfalling hurricane. This model can be exercised worldwide at the first indication of threatening tropical storm activity.

With the parametric wind model in hand, a hurricane storm surge prediction system has been developed to automate the forecast of surge and inundation in coastal regions (Fig. 8). The system, initially based on the hindcast of Hurricane Katrina, can address storms poised to strike the Mississippi Gulf Coast. Analysis and forecast data from the NOAA National Weather Service National Hurricane Center/Tropical Prediction Center forecast/advisory files are automatically read and processed. Extracted data, such as time and date information, tropical storm position, estimates to the radius of maximum winds, and the central pressure of the storm for analysis and forecast time periods, initializes the generation of forecast cyclone winds using the Holland model. These wind fields are then interpolated onto the finite element mesh providing the meteorological forcing for execution of the ADCIRC storm surge model. This system, presently designed for Gulf Coast applications by virtue of the mesh location, was transitioned to NAVOCEANO on May 10, 2006, in time for the 2006 Atlantic hurricane season.

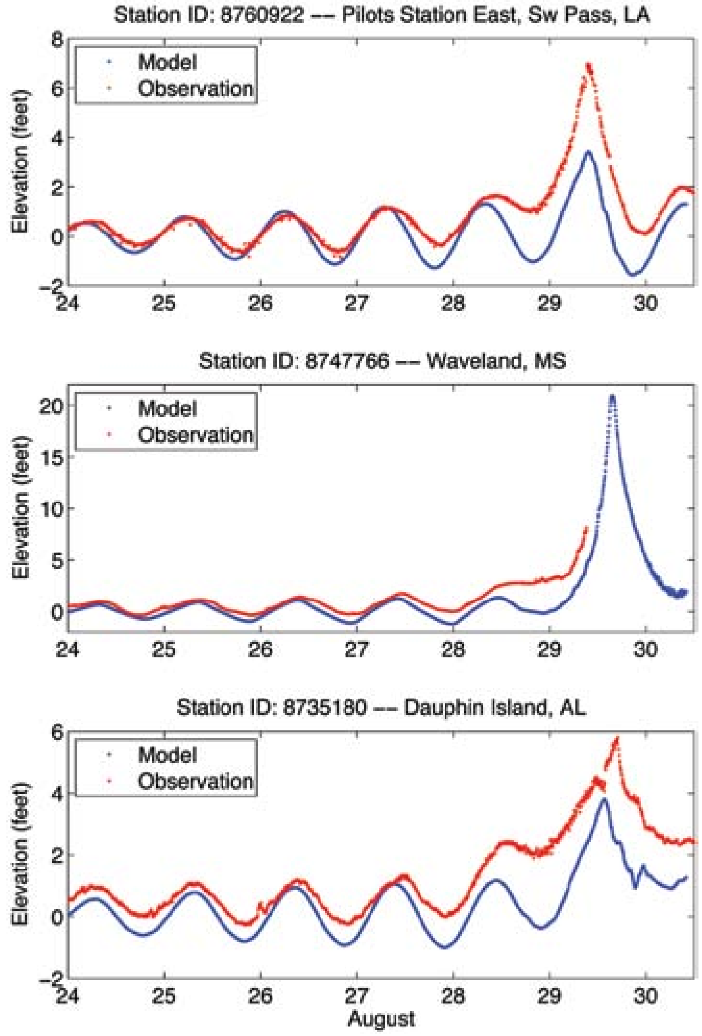

FIGURE 5
Time series of model-computed (blue) and observed (red) water elevations in feet at three NOAA coastal stations, Pilot Station East, SW Pass, Louisiana, Waveland, Mississippi, and Dauphin Island, Alabama.

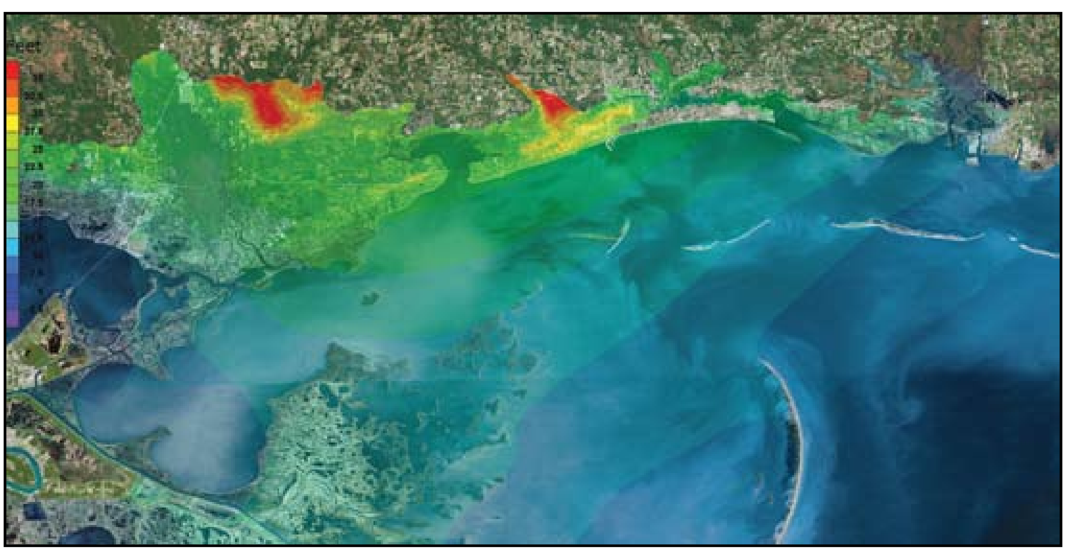

FIGURE 6
A map of modeled high water mark values (feet) obtained from evaluations at every 1-second model time-step during the hindcast of Hurricane Katrina.

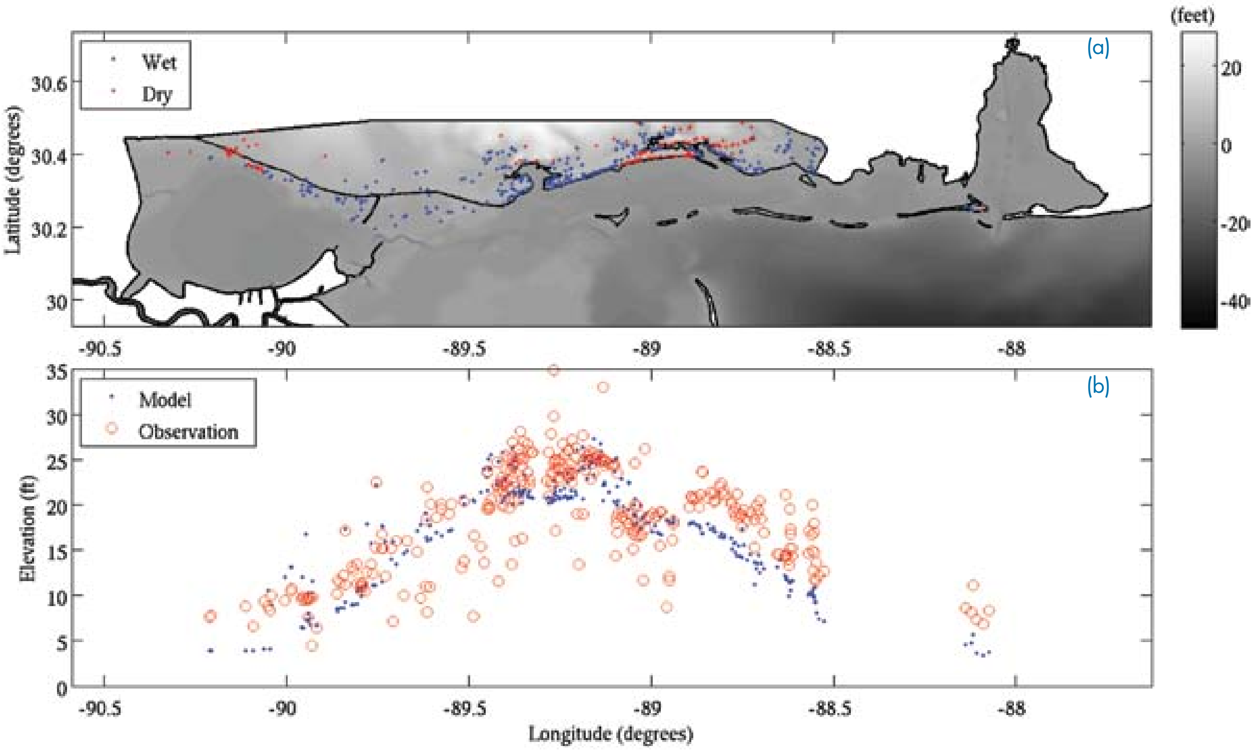

FIGURE 7
(a) A map of inundated (blue) or dry (red) USGS high water mark locations as computed by the model. (b) Comparisons of the modeled (blue) and measured (red) high water elevations in feet at 315 USGS stations.

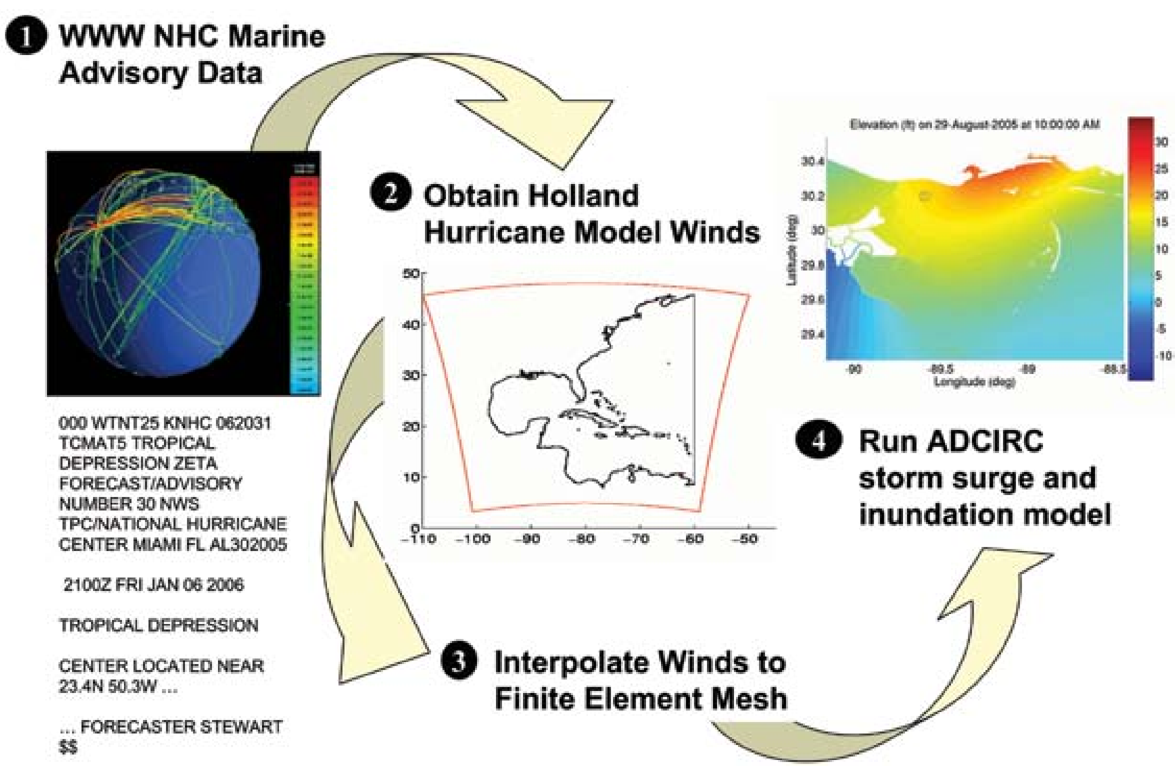

FIGURE 8
A schematic of the developed storm surge and inundation prediction system transitioned to the Naval Oceanographic Office at Stennis Space Center, Mississippi, in May 2006.

The ability to rapidly apply the ADCIRC surge model to any location globally is the ultimate goal of a surge forecast prediction system. Continued refinement of the mesh generation tool created at NRL into a fully automated operation is making that goal possible. Experience gained during the hindcast of Katrina has motivated a number of improvements in the mesh generation capability. A multi-stage mesh generation approach is often advantageous to balance resolution requirements and computational limitations in different regions of the mesh. For this approach, the ability to "stitch" together different meshed regions was developed. A series of mesh quality adjustments are now automatically applied to a created mesh to eliminate poorly constructed triangular elements that may cause model instabilities. Furthermore, an estimate of model computational time is provided based on the size of a created mesh. The user can decide if iterations on the mesh design are needed, knowing current operational constraints.

Our experience, and that of others, modeling the inundation from Katrina indicates that fine-scale information on overland elevation, vegetation type, and frictional characteristics are all very important for accurate representation of a wetting front. Methods are now being developed to automatically extract such information from remotely sensed imagery and utilize it in the mesh generation process. Achieving a fully automated mesh generation capability will expand application of our developed storm surge and inundation prediction system to worldwide inundation events.

Apart from the mesh generation process, our analyses of Hurricane Katrina surge and inundation hindcasts highlight improvements to the inundation methodology that could result in even more accurate, robust forecasts. For example, the movement of water inland would be better represented as a response to not only water elevation and frictional effects but also wind forcing. The conservation of water in overland regions that are wet, dried, and rewet is another important aspect. In addition, tracking and resolving the wet-dry interface would further enhance fidelity of the inundation forecast.

The challenge at NRL is not only to develop the most advanced and accurate modeling technology but also to facilitate its transition into an operational framework whose priorities are often ease of use and quick turnaround of operational products. The hindcast of Hurricane Katrina's storm surge and inundation provides the opportunity for progress in both realms.

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